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MEASUREMENT OF DROPLET SIZE & VELOCITY USING A PHASE DOPPLER ANEMOMETER

Report No 86-320-K

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ABSTRACT

The application of Laser Doppler Anemometry to droplet size and velocity measurements was investigated. After reviewing various methods based on light scattering, the Phase Doppler Anemometer (PDA) was chosen for verification. The droplet size standard was a monodisperse droplet generator. Its capability of generating a stream of uniform size droplets was verified with photographs. The theory of operation for the PDA and a design criteria for the optical detector are given. It was shown that velocity measurements could be based on the single-phase LDA theory. The droplet sizing capabilities of the PDA were evaluated by measuring the monodisperse droplets. The results of the verification show that the PDA is a useful tool for the non-intrusive measurement of droplet size.

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EXECUTIVE SUMMARY

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Dispersed two-phase flows occur in nuclear and thermal power stations. These include particles borne by flue gas or air in ductwork associated with fossil-fired boilers, water droplets borne by steam in post-dryout flows and the dispersion of aerosols in a nuclear containment system. To better understand these flows, instrumentation is required for particle or droplet size and velocity measurement. This report describes the evaluation of various instruments for droplet size and velocity measurement and the validation of a promising instrument, the Phase Doppler Anemometer.

The droplet-sizing capabilities of the Phase Doppler Anemometer (PDA) were verified by measuring droplets of a known radius. The droplets, which ranged in size from 250 lm to 1200 lm, were produced by a monodisperse droplet generator. Its high accuracy was verified photographically. Droplet size measurements by the PDA agreed to within 25% of the size standard produced by the droplet generator. Although this accuracy is acceptable for many applications, a design criterion for the optical detector is given from which an instrument having a higher accuracy and wider range may be developed. It was shown that the theory describing the velocity measurement of droplets reduced to the universal equation for LDA in single-phase flows for the optical configuration and droplet sizes described herein. Since the application of LDA to single-phase flow velocity measurements is well established and verified, droplet velocities were not verified in this study.

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To Dr. D. Mills
Director of Research

MEASUREMENT OF DROPLET SIZE & VELOCITY
USING A PHASE DOPPLER ANEMOMETER

1.0 INTRODUCTION

Dispersed two-phase flows occur in nuclear and thermal power stations. Some examples are particles borne by flue gas or air in ductwork associated with fossil-fired boilers, water droplets borne by steam in post-dryout flows and the dispersion of aerosols in a nuclear containment system. In all cases, there is a need to quantify the particle velocity and size distribution. This data can then be used to design equipment for the control of airborne particles or to evaluate a transport mechanism involving chemicals or heat.

The instrumentation required for measurements in dispersed two-phase flow must be non-intrusive, accurate, have a good spatial resolution and have a high data acquisition rate. Laser Doppler Anemometry (LDA) is a non-intrusive measurement system which is well established for velocity measurements in single-phase gaseous and liquid flows/1/. To date, extensive research has been devoted to the application of LDA in two-phase flows/2/. Droplet and particle sizing constitute a large portion of this research. Therefore, a feasibility study on the application of LDA for measurements in two-phase dispersed flows is warranted.

This report describes a co-operative program between the Thermo-Fluids Unit, Ontario Hydro Research Division and the Laser Doppler Anemometry Laboratory, University of Toronto. The objectives of the program were to acquire new expertise in droplet size measurements using LDA, to select the most suitable technique to be applied in two-phase dispersed flows and to verify its operation. A review of droplet sizing instrumentation is given in Section 2.0. Section 3.0 describes a device for the generation of uniform size droplets. All aspects of the droplet sizing measurements including theory of operation, detector design and verification are described in Section 4.0.

2.0 DROPLET SIZING INSTRUMENTATION

The types of instrumentation which meet the qualifications for droplet sizing in dispersed two-phase flows are evaluated. The two major techniques can be categorized as imaging and light scattering.

2.1 Imaging Techniques

Imaging techniques include still photography, high speed photography, and video recording. All of these methods are non-intrusive but the spatial resolution will depend on the focussing optics used. The accuracy of these methods will depend on the size of the droplet in reference to the field of view. However, the relative simplicity of imaging techniques make them useful for visualizing the flow. Using high speed photography or video recording, a steady state or transient dispersed flow may be visualized over a large area. This is useful for obtaining first estimates of droplet velocity and size distributions. With the use of computer-aided image analysis techniques, visual records can be analysed to yield more accurate data. However, the process is time consuming.

2.2 Light Scattering Techniques

Light scattering techniques for droplet sizing can be classified as amplitude discrimination, optical gating, and phase Doppler anemometry. Following is a brief description of each method.

Amplitude Discrimination: This technique is based on the premise that the droplet size is a monotonic function of the scattered light intensity. This will be the case if the illumination is uniform in intensity and the light is collected over a wide range of angles. This method has been applied successfully by using laser illumination and by electronically selecting light scattered from the uniform central core of the laser beam/3/. In another application, a uniform intensity donut-shaped beam was produced using a laser operating in the TEM_{01} mode/4/. Amplitude discrimination techniques require calibration to determine the dependence of measured light intensity on droplet size. Care must also be taken to prevent any light attenuation between the measuring volume and the collection optics. This may be caused, for example, by a window in a test section.

Optical Gating: This technique requires the measurement of droplet velocity and the time of passage to determine the droplet size. The accuracy of this method depends upon the accuracy of the velocity measurement and uniform illumination of the droplet. For the case of illumination with a Gaussian laser beam, the droplet must pass through the center of the measuring volume where the intensity distribution is close to uniform. For the latter reason, this technique is best suited for droplets which are much larger than the size of the measuring volume. An example of the gating technique is given in reference/5/. The single beam from the laser was split into two equal intensity beams and focussed at the point of measurement. The intensity of one of the beams was monitored. When a large droplet intersected this beam, the passage of light to the detector was interrupted. The velocity Doppler signal was measured by collecting the light scattered by the droplet at the intersection of the two beams. A different approach to gating was to create a set of fringes in space using Ronchi grating/6/. As the droplet intersected the measuring volume, light was scattered from the fringes. The frequency of this signal was used to calculate the droplet velocity. The time of the droplet passing through the measuring volume was detected by a slot of optical fibres. Knowing the droplet velocity and the time of passage, the droplet size was calculated. Accurate optical alignment requiring three access points was necessary to define the measuring volume and to ensure the droplet center passed through the measuring volume.

Phase Doppler Anemometer (PDA): This technique is based on the fact that light from two intersecting laser beams scattered by a particle will interfere to form fringes in space on a screen or optical detector. It can be shown from geometrical optics, that the fringe spacing is proportional to the particle size given that the detector is far from the measuring volume and the beam crossing angle is small/7/. Although the optical detector can be placed at any scattering angle, only forward scatter will be considered in this report. The velocity of these fringes, determined from the signal frequency, is proportional to the particle velocity. Both the fringe spacing and the fringe velocity may be measured with at least two photodetectors mounted close together. Recently, there has been increased interest in this particle sizing method because it has a wide dynamic range, it is insensitive to optical disturbances, it has a high accuracy and for most cases the instrument response is independent of particle trajectory/8/.

Considering the advantages and disadvantages of these three methods of droplet sizing, the phase Doppler anemometer was selected for detailed study and verification. The remainder of this report describes the theory of operation for the phase Doppler anemometer (PDA), the design of an optical detection system, and verification of the technique with a droplet size standard.

3.0 MONODISPERSE DROPLET GENERATOR

For evaluation of the accuracy and range of the Phase Doppler Anemometer, a droplet size standard is necessary. A monodisperse droplet generator fits the requirements because it can produce a stream of uniformly sized droplets over a wide range of sizes.

The monodisperse droplet generator works on the principle that when vibration is imposed upon a laminar liquid jet, the droplets will fall at regular intervals. In doing so, each droplet contains the same volume of fluid and hence has the same radius. For a given tube diameter and flowrate there are certain frequencies which cause uniform droplet breakup.

Experience has shown that for a laminar jet 5 diameters long, droplets of approximately twice the jet diameter will form/9/. The droplet breakup results from instabilities in the laminar jet. However, these instabilities are somewhat random causing the droplet size to vary. By imposing a frequency on the flow close to the natural droplet breakup frequency, a uniform stream of droplets can be produced. For a jet with diameter, d, and velocity, v, the natural frequency of droplet formation is near v/5d. The droplet diameter can be adjusted somewhat by varying the forcing frequency, but to produce a wide range of droplet sizes, nozzles of different diameters are required.

The main components used for generating the monodisperse droplets were a glass tube and an audio speaker. The glass tube acted as the flow nozzle. The speaker was used to impose a vibratory excitation of the desired frequency on the flow in the tube. The glass tube was bent into an L-shape and glued to the speaker as shown in Figure 1. The flow of water to the tube was controlled by a water regulator and a needle valve. A Krohn-Hite Model 5100A signal generator produced sufficient output to drive the speaker.

The droplet size can be determined either photographically or by calculation given the operating conditions. The photographic method is time consuming yet accurate. Therefore, it is useful for checking the accuracy of the calculation method. Alternatively, the calculation method is simple and fast. Consequently, photography was used to verify the calculation method and thereafter, the calculation method was used to determine the droplet size produced by the monodisperse droplet generator. The required parameters for calculating the droplet size are the fluid flowrate and the forcing frequency. The equation for the droplet radius is given by:

$$R = 3 \sqrt{\frac{V}{80 \pi f T}} \qquad (1)$$

where V = the amount of liquid [ml] collected in time T [min]

f = vibrational frequency of the nozzle [Hz]

R = the droplet radius [m]

The accuracy of this method can be evaluated by performing an error estimate:

$$\frac{\Delta R}{R} \approx \frac{1}{R} \left(\frac{\partial R}{\partial V} \Delta V + \frac{\partial R}{\partial T} \Delta T + \frac{\partial R}{\partial f} \Delta f \right) \qquad (2)$$

evaluating the differentials and substituting:

$$\frac{\Delta R}{R} \approx \frac{1}{3} \left(\frac{\Delta V}{V} - \frac{\Delta f}{f} - \frac{\Delta T}{T} \right) \qquad (3)$$

Using some typical values, V = 6.0 ml, f = 250 Hz, T = 1.0 min, and given the tolerances, $\Delta V = \pm 0.05$ ml, $\Delta f = \pm 0.5$Hz, $\Delta T = \pm 0.008$ min,

$$\frac{\Delta R}{R} = 0.0006 \qquad (4)$$

The droplet size, as predicted by equation (1), was verified photographically. Streams of uniformly sized droplets were produced, ranging in size from 250 to 1200 microns radius. For each size of droplet, the droplet stream was photographed using a flash unit for illumination. The photographed droplets were measured by projecting the negative on a screen and measuring the image with a vernier caliper. A scale was also photographed alongside the droplet stream so that the image size could be converted to the actual droplet size (see Figure 2). The droplet sizes determined by photography were compared with the calculation method. Tables 1-3 and Figure 3 show the results. The two methods of determining the droplet size show excellent agreement.

4.0 PHASE DOPPLER ANEMOMETER

4.1 THEORY OF OPERATION

The theory for the phase Doppler anemometer is based on light scattering using the geometric optics approach. It is assumed that light can be modelled as a ray which will be governed by the laws of reflection and refraction. Glantschnig & Chen/10/ have shown that the geometric optics approach, when used to calculate light scattering in the forward direction from a droplet, can be applied if the droplet is greater than 5 microns radius. For the purposes of this analysis, it will be assumed that the phase Doppler anemometer is operating in the forward scatter mode.

The theory of operation for the Phase Doppler Anemometer working in forward- or back-scatter was first reported by Durst and Zare/7/. However, it is useful to present the detailed derivation based on ray tracing to better understand the limitations of the resulting equations. Consider a spherical droplet onto which two laser beams are focussed. The problem is to calculate the fringe spacing of the scattered light on a plane perpendicular to the plane of the laser beams and at a distance, L, in the forward scattering direction. The solution proceeds by assuming that the laser beams are rays of light and that these rays exist only on one plane. Then the problem is reduced to two dimensions as shown in Figure 4. Let the half-angle between the two rays leaving the droplet be represented by beta. Given this angle, the distance between the interference fringes can be calculated from the fringe spacing equation for an LDA measuring volume/1/. The equation is given by:

$$\Delta x = \frac{\lambda}{2 \sin \beta} \qquad (5)$$

Since β is unknown, it must be related to the half-angle ψ. Using the Snell's law and trigonometry, the functional relationship for ψ is given by:

$$\psi = 2\sin^{-1}\left(\frac{\eta_a}{\eta_w}\frac{L}{R}\sin\beta\right) - 2\sin^{-1}\left(\frac{L}{R}\sin\beta\right) + \beta \qquad (6)$$

β must be isolated so that this equation is more useable. This is possible if sin β is replaced by β. This is permissible for small values of β. Substituting β for sin β in the above equation yields:

$$\psi = \left[\frac{2L}{R}\left(\frac{\eta_a}{\eta_w} - 1\right) + 1\right]\beta \qquad (7)$$

Substituting equation (7) into equation (5) and assuming that $\psi = \sin \psi$ yields the equation for the fringe spacing for two beams transmitted through a sphere:

$$\Delta x = \left[1 + \frac{2L(\eta_a - 1)}{\Sigma \eta_w}\right] \frac{\lambda}{2 \sin \psi} \tag{8}$$

The fringe spacing may be measured by mounting two photo detectors side-by-side in front of the measuring volume at a distance L. The spacing of the detectors, normal to the fringes, Δ a sin α must be less than the minimum fringe spacing expected to be measured. The fringe spacing is then calculated from:

$$\Delta x = \frac{\Delta a \sin \alpha}{\phi} \tag{9}$$

where ϕ = the phase shift between the Doppler signals measured by each of the photodetectors

α = the angle between a line connecting the photodetectors and a line parallel to the fringes

The velocity of the droplet passing through the measuring volume can be derived from vector analysis and geometric optics. When two laser beams are transmitted through a moving droplet, each of the beams is refracted at both interfaces (entering and leaving). For a simple case of a sphere with no rotational movements, the Doppler frequency detected in the forward direction was formulated as/7/:

$$f_D = \frac{2 U (\sin \psi - \sin \beta)}{\lambda} \tag{10}$$

It can be seen from equation (7) that when L/R is large then $\beta << \psi$. For this case, equation (10) tends towards the universal equation of laser Doppler anemometry for single phase velocity measurements. Since single-phase flow velocity measurements using LDA is well established, droplet velocity measurements were not verified.

4.2 DESIGN OF DETECTION SYSTEM

To design a double-diode detection system for droplet sizing, it is necessary to know the intensity and frequency of the scattered light incident on the diodes. The frequency of the scattered light is dependent upon the velocity of the droplet while the scattered light intensity is dependent upon the droplet size. Although the range of droplet sizes and velocities will depend on the application, a wide range will be selected to demonstrate the method of design.

There are many other parameters which are required to calculate the scattered light intensity and frequency. These are: the laser wavelength, the laser beam crossing angle, the distance from the measuring volume to the photodetector and the liquid refractive index. These parameters were held constant by selecting one optical configuration, so that the effect of varying droplet size on scattered light intensity could be evaluated. The optical configuration in the present study included a Spectra-Physics Model 124A 15 mW He-Ne laser. The beam separation was 50 mm and the focussing lens had a focal length of 300 mm. The double diode detector was mounted 300 mm from the measuring volume in the forward scattering direction. The liquid was water in all cases. Given this setup, the following parameters are known:

λ = the wavelength of the laser = 632.8 nm

ψ = the beam crossing half-angle = 4.78°

L = the distance from measuring volume to detector = 300 mm

η_W = the refractive index of water = 1.33

The range of light scattering frequencies can be estimated from the universal equation of laser Doppler anemometry for single phase measurements:

$$f_D = \frac{2\ U \sin \psi}{\lambda} \qquad (11)$$

For example, given typical droplet velocities of 50-200 cm/s, the Doppler frequencies for this optical arrangement would fall in the range of 100-500 kHz. The Datalab DL 1080 Programmable Transient Recorder, used for the verification tests, can sample at rates of up to 20 MHZ.

The intensity of the scattered light for a range of droplet sizes is necessary to specify the sensitivity of the photodetector. Again, the problem is illustrated by two laser beams separated by a crossing angle, ψ and focussed on a droplet. The scattered light can be detected most conveniently in either the forward or backward direction. In forward-scattering the intensity of light is greatest but maintaining alignment between the forward and receiving optics may be a problem if the PDA must be traversed. In back-scattering mode, the intensity of light is least but realignment of the optics is unnecessary because they are mounted in one package.

To calculate the intensity of light scattering from a droplet, the wave nature of light must be considered, specifically the constructive and destructive interference of light scattered from many angles and combining on the detector surface. This problem may be simplified by considering the two laser beams to be the superposition of two single laser beams. This reduces the calculation to light scattered from a droplet which is illuminated by a monochromatic beam with a gaussian intensity distribution. A solution to this problem was given by Ferguson/11/ and a calculation for light scattered from a 250 micron droplet will be shown later. However, this problem may be simplified further by assuming that the droplet is illuminated by a beam of infinite width and a uniform intensity distribution. The solution to this problem was first obtained by Mie/12/ and a good description of the solution is given by van de Hulst/13/. The assumption of uniform intensity illumination approaches reality when the droplet is much smaller than the width of the laser beam. For example, the intensity of a 1 mm diameter laser beam only drops to 95% of the centerline intensity at a distance of 0.08 mm from the centerline. Using the Mie scattering solution in this example for droplets of 80 microns radius or greater, would give scattering intensities greater than if the scattering were based on Gaussian illumination. Although the solution to the Mie scattering problem is well documented, the solution requires extensive computations. Since the solution is calculated by the summation of series, the number of summations required for convergence is proportional to the size of the particle. Fortunately, a geometric optics approximation to the Mie solution was developed by Glantschnig & Chen/10/ for the case of forward scattering. Therefore, there are three methods of solution to this light scattering problem. From these, it is possible to calculate the scattered light intensity on a double-diode detection system as a function of droplet size.

The University of Toronto Laser Doppler Anemometry Laboratory (LDAL) in the Department of Mechanical Engineering has an OEI Model LD-OP801 double-diode detection system. This detector system was used together with a 15 mW He-Ne LDA in forward scatter mode for droplet sizing. Therefore, it was of interest to calculate the scattered light intensity for this detector system. Figure 5 shows the optical arrangement. Each diode had an active surface with dimensions 500 x 500 microns. The center-to-center spacing of the diode pair was 6.5 mm. It was assumed that the line intersecting the centers of the diodes was parallel to the plane of the laser beams. For calculation purposes, the active area of the diode was sub-divided into a 20 x 20 grid of equal areas. Due to symmetry about the plane of the laser beams, only a 10 x 20 grid needed to be calculated. The intensity of light scattered to each diode is equal for this case so only one diode needed to be considered. The calculation procedure involved the

determination of the light scattering amplitude function for each grid point. Light was being scattered from two laser beams at different angles so two separate calculations were required. The corresponding amplitude functions for each grid point were added and from this value the light intensity was calculated. The total light incident upon the detector surface was integrated over the 400 grid points.

A comparison of the three methods of light scattering calculation are shown in Table 4. The droplet size was 250 microns and the laser light had a parallel polarization. From the table, it is apparent that for backscattering the Mie and Gaussian scattering calculations produced similar results. However, in the case of forward scattering, the geometric and Mie scattering calculations produced results somewhat greater than those produced by Gaussian scattering. This is understandable, when considering that the latter calculation uses a gaussian light intensity distribution and with a 250 micron droplet, the incident intensity at the droplet perimeter is 60% of that at the center.

The scattered light intensity as a function of droplet radius is plotted in Figure 6. The calculations were based on Mie scattering. Therefore it should be kept in mind that these results will show intensities greater by 25 or 30% for droplets of 250 to 1000 microns as compared to scattering by Gaussian illumination. It can be seen that the polarization of the incoming light does not greatly affect the detected intensity. For droplet radii less than 50 microns the intensity drops off rapidly. Given a range of droplet sizes, this figure may be used to estimate the upper and lower bounds on the optical power incident on the detector. If a He-Ne laser with a power other than 15 mW is used, the detector incident power can be scaled by the ratio of laser powers. If a detector area other than 250×10^{-9} m^2 is used, then to a first approximation, the detected optical power is proportional to the detector area. (The difference is due to the fact that the integrated light intensity will vary somewhat over the small changes in angle).

Another parameter to consider in specifying the detector system is the center-to-center spacing between the diodes. To ensure that the phase shifts of the signals coming from the two detectors is measured accurately, the spacing between the diodes should be less than the fringe spacing corresponding to the largest expected droplet size. For example, given a droplet of 1000 micron radius and the specified optical setup, the fringe spacing as calculated from equation (8) is 0.56 mm. Therefore, the diode spacing must be less than this value. Practically speaking, no two diodes housed in separate cans could be mounted this close together, so the best approach is to mount the diodes

on a cannister which rotates around the optical axis. The cannister can be graduated in degrees of rotation with zero degrees corresponding to the diodes lining up perpendicular to the plane of the laser beams (see Figure 7). Given a diode spacing of 6.5 mm, the diode angle, α, would have to be set to 5°. A smaller diode spacing would be preferable for this application because it would allow for a larger diode angle and hence a greater resolution for droplet sizing. If the diode spacing could be reduced to 2 mm, say by mounting two diodes into one can, the diode angle could be increased to 16°.

4.3 EXPERIMENTAL VERIFICATION

A Phase Doppler Anemometer (PDA) was set up in the University of Toronto Laser Doppler Anemometry Laboratory to verify its droplet sizing capabilities against a monodisperse droplet generator.

The monodisperse droplet generator was capable of producing droplets ranging in size from 250 microns to 1200 microns radius. This wide size range was obtained by using four sizes of glass tube for the nozzle. It was found that the droplet radius was approximately equal to the diameter of the nozzle. Consequently, the glass tubes ranged in size from 250 microns to 1000 microns diameter. The water flowrate through the nozzle was controlled with a water pressure regulator and a needle valve. The regulator was connected to the domestic water supply and the needle valve was connected in series between the regulator and the nozzle. The vibration of the speaker was controlled by connecting the 5 volt square wave output of the signal generator directly to the terminals of the speaker coil. A Data Precision Model 5845 frequency counter was connected to the low level output of the signal generator to accurately measure its frequency. A strobe light was used to illuminate the droplet stream. The operating procedure of the droplet generator was as follows:

1. Adjust the water regulator to 10 psig.

2. Adjust the needle valve to obtain 5 nozzle diameters of laminar flow between the nozzle tip and the point where breakup occurred.

3. Apply a frequency to the speaker and, using the strobe light for viewing the droplet stream, adjust the frequency until a uniform size of droplets appear.

By using different combinations of nozzle diameters and frequency settings, a range of droplet sizes could be produced. Table 5 gives the range of frequencies and droplet sizes corresponding to each nozzle.

The droplet size was determined from the frequency of the speaker and the flowrate through the nozzle. A graduated cylinder was placed under the droplet stream for a period of 15 to 60 seconds. The volume and time were recorded. The frequency as indicated by the frequency counter was also recorded. The volume, time and frequency were used in equation (1) to calculate the droplet radius.

The phase Doppler anemometer included the optical arrangement as previously described, the double diode detector, signal processors and the data acquisition system. Figure 8 shows the optical arrangement. A collection lens with a 300 mm focal length was used to collect light scattered from the measuring volume. Given that the diode spacing was 6.5 mm, the diode angle was set to 5° to allow measurements of droplets up to 1000 microns radius. The signal from each diode was preamplified and then bandpass filtered. The filter settings were 31.5 kHz high pass and 1 MHz low pass. These settings removed all but the Doppler frequency which was around 400 kHz. After passing through the filters, the signals were connected to the inputs for channel 1 and channel 2 of the waveform recorder (Figure 9). The magnitude of the signals at this point ranged from 0.1 to 0.2 volts peak-to-peak depending on the droplet size. The waveform recorder was set to digitize the Doppler signals at a sampling rate of 20 MHz. The data buffer for each channel held 4096 points and the amplitude resolution was 8 bits. The two data buffers were transferred to a PDP 11/03 micro-computer through the IEEE 488 interface for online data reduction.

Software was developed for data acquisition from the waveform recorder and for reduction of the two Doppler bursts to a frequency and a phase shift. The computer was instructed to wait until the waveform recorder data buffers were filled and then to transfer the data to its Random Access Memory (RAM). After the data was reduced, the computer armed the waveform recorder to accept another set of bursts. A typical set of bursts is shown in Figure 10.

The data reduction algorithm used by the software implemented the frequency validation scheme recommended by Tropea and Venkatesh, LSTM Erlangen, FRG/14/. The frequency of the burst was calculated by counting a number of zero crossings and measuring the time duration. Initially, two cycles of the burst had to exceed a minimum amplitude level before counting commenced. The burst was accepted if at least a specified number of zero crossings were accepted. After burst acceptance, subsequent zero crossings were counted until the end of the burst or record whichever came first. Two frequencies were calculated, based on the acceptance number and the total number of zero crossings. The burst frequency was considered valid if the two frequencies fell within

a specified tolerance. The phase shift between bursts was determined by measuring the time delay between corresponding zero crossings. Given that both bursts were stored in a one-dimensional array of 8192 elements, a corresponding zero crossing was found by adding 4096 to the address of a zero crossing in channel 1 and incrementing the address until a zero crossing was found in channel 2. By this method, a phase shift was calculated for each set of corresponding zero crossings. Two average phase shifts were calculated based on the acceptance range and the total range of zero crossings. The phase shift calculation was valid if the two phase shifts agreed within a specified tolerance.

The data rate for this type of measurement was based on the transmission time for the IEEE 488 interface, the speed of the computer and the ratio of accepted bursts to recorded bursts. Considering a 100% acceptance ratio, 20 pairs of bursts could be collected in two minutes. However, it was not uncommon to have an acceptance ratio of only 50%. To increase the data rate, the interface transmission rate and computer speed must be increased. Of these two, the greatest increase in data rate could be acheived by modifying the interface software or hardware. One possibility is to use the Direct Memory Access (DMA) option on the IEEE interface. This would increase the data transmission rate by 100 times. Another option is to identify a micro-computer system for which a waveform recorder board could be plugged into one of the I/O slots.

Four series of validation tests were performed using each of the four nozzle diameters as mentioned above. For each series of tests, a range of droplet sizes was produced. When a monodisperse droplet stream was produced, the nozzle was traversed such that the droplets fell through the optical measuring volume. An oscilliscope was connected to the waveform recorder to view the bursts as they were received. If the bursts appeared satisfactory, then the data acquisition was initiated. The computer was instructed to record on floppy disk the frequency and phase for 20 acceptable burst pairs. While the data acquisition was in progress, the nozzle flowrate and speaker frequency pertaining to the droplet generator were measured. After the computer finished data collection, the file containing the frequency and phase data was printed out. A programmable hand calculator was used to calculate the droplet radius and the results were recorded by hand. Tables 6 to 9 show the results of all the tests. The droplet radius, as measured by the PDA, was plotted against the actual value (see Figure 11). There is good agreement between the PDA measurement and the actual values. The data appears to be randomly scattered and the maximum error is 25%.

5.0 CONCLUSIONS & RECOMMENDATIONS

This validation has shown the feasibility of using a low power laser and a simple optical arrangement for sizing single droplets. Considering the voltage output from the diodes and the light scattering calculations (Figure 6), it is estimated that with the current optical arrangement, droplets as small as 50 microns radius could be detected and measured. The upper size range, 1000 microns radius, was limited by the diode spacing. It has been shown that the universal equation of LDA (11) may be applied to velocity measurements of droplets ranging in size up to 1000 microns radius for the optical arrangement used in this study.

The following would improve the accuracy and performance of this instrument:

1. A high-sensitivity double-diode detector with active elements spaced 2 mm apart.

2. Increased data transmission rate for the interface between the waveform recorder and the computer, or a computer system with integral waveform recorders.

Further study of the Phase Doppler Anemometer (PDA) is required to evaluate its applicability for droplet sizing in sprays, aerosols and particle-laden air flows. Verification of the technique for aerosols would require a Berglund-Liu monodisperse droplet generator which can produce droplets ranging in size from 1-200 microns. Evaluation of the technique in polydisperse aerosols would require an aerosol spray nozzle. A comparison of the droplet size distribution in the spray could be made with measurements using an imaging technique. Having verified the operation of the PDA for these types of flows, the instrument will be ready for application to dispersed two-phase flows.

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Approved:

G.J. Clarke
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IGE:sf

Submitted

I.G. Elphick
Engineer
Mechanical Testing and
Development Section

List of Symbols

f = vibrational frequency of the nozzle

f_D = Doppler frequency of light scattered from the droplet

L = distance from the measuring volume to the detector

R = the droplet radius

T = collection time of liquid from droplet generator

V = volume of liquid collected from droplet generator

U = component of the droplet velocity perpendicular to the optical interference fringes

α = angle between a line connecting the photodetectors and a line parallel to the optical interference fringes

β = beam crossing half-angle of the refracted light

Δa = diode center-to center spacing

Δx = interference fringe spacing of light at LDA measuring volume

η_a = refractive index of air

η_w = refractive index of water

λ = wavelength of the laser light

ϕ = the phase shift between two Doppler signals

ψ = beam crossing half-angle of the incident light

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Table 1: MDG Validation - NOZZLE #4

FILL [ml]	TIME [s]	FREQUENCY [Hz]	Rmdg [μm]	Rpic [μm]
6.8	60	365	420	483
6.8	60	412	403	421
6.0	60	554	351	375
7.6	60	630	363	373

Table 2: MDG Validation - NOZZLE #2

FILL [ml]	TIME [s]	FREQUENCY [Hz]	Rmdg [μm]	Rpic [μm]
6.5	30	212	625	645
7.4	30	213	651	635
7.5	30	241	628	664
7.4	30	269	603	581
6.8	30	370	527	509
8.2	15	1116	489	479
8.6	15	858	542	514
8.2	15	703	570	540
8.2	15	703	570	565

Table 3: MDG Validation - NOZZLE #1

FILL [ml]	TIME [s]	FREQUENCY [Hz]	Rmdg [μm]	Rpic [μm]
8.3	15	90	1140	1103
8.0	15	90	1120	1123
8.5	15	94	1130	1121
8.6	15	94	1130	1123
8.2	15	112	1050	1061
8.1	15	112	1050	1058
10.0	15	122	1090	1071
7.0	15	115	989	980

Table 4: Power of Scattered Light on One Diode

Method of Calculation	Forward Scatter [W]	Backscatter [W]
Geometric Scattering	3.614×10^{-9}	-
Mie Scattering	2.421×10^{-9}	4.393×10^{-11}
Gaussian Scattering	1.908×10^{-9}	4.311×10^{-11}

Table 5: Monodisperse Droplet Generator, Size Ranges

Nozzle Diameter [μm]	Speaker Frequencies [Hz]	Droplet Radii [μm]
#1 1000	95 - 120	1074 - 1001
#2 450	211 - 1067	639 - 474
#3 350	292 - 1386	508 - 389
#4 250	264 - 898	449 - 272

Table 6: DROPLET SIZING VALIDATION - NOZZLE #4

ALPHA [deg]	FILL [ml]	TIME [s]	FREQUENCY [Hz]	PHASE [cycles]	Rpda [μm]	Rmgd [μm]
5	3.7	30		0.284	285	360
5	7.8	60	659	0.272	273	361
5	8.2	60	1128	0.221	222	307
5	6.2	60	479	0.286	287	372
5	6.2	60	587	0.315	316	348
5	6.6	60	588	0.325	326	355
5	6.4	60	587	0.385	387	351
5	6.5	60	587	0.371	373	353
5	5.2	60	246	0.486	489	438
5	6.2	60	352	0.402	404	412
5	6.3	60	352	0.480	483	415
5	6.2	60	351	0.436	438	413
5	6.2	60	351	0.450	452	413

Table 7: DROPLET SIZING VALIDATION - NOZZLE #3

ALPHA [deg]	FILL [ml]	TIME [s]	FREQUENCY [Hz]	PHASE [cycles]	Rpda [μm]	Rmgd [μm]
5	8.0	60	183	0.484	487	558
5	8.1	60	183	0.456	458	561
5	8.1	60	183	0.437	439	561
5	7.8	60	289	0.489	492	475
5	7.9	60	288	0.501	504	478
5	8.2	60	289	0.487	490	483
5	11.0	60	711	0.457	459	395
5	5.6	30	712	0.471	473	397
5	5.6	30	711	0.459	461	397
5	5.7	30	711	0.438	440	400
5	6.9	30	711	0.444	446	426
5	6.6	30	711	0.476	478	420
5	6.6	30	711	0.419	421	420
5	6.6	30	711	0.408	410	420
5	6.5	30	743	0.406	408	411
5	4.0	30	182	0.393	395	559
5	8.0	60	182	0.466	468	559
5	8.	60	182	0.633	667	559
5	8.0	60	183	0.489	492	558
5	9.4	69	183	0.608	612	562
5	8.0	60	183	0.561	564	558
5	8.0	60	183	0.637	641	558
5	4.0	30	183	0.418	420	558

Table 8: DROPLET SIZING VALIDATION - NOZZLE #2

ALPHA [deg]	FILL [ml]	TIME [s]	FREQUENCY [Hz]	PHASE [cycles]	Rpda [μm]	Rmgd [μm]
5	7.6	30	286	0.630	634	596
5	7.6	30	287	0.693	698	595
5	7.7	30	287	0.634	638	598
5	7.8	30	286	0.660	664	601
5	7.6	30	287	0.591	595	595
5	7.7	30	384	0.521	524	542
5	7.6	30	384	0.557	560	540
5	7.8	30	384	0.552	555	545
5	7.7	30	385	0.572	575	542
5	7.6	30	385	0.554	557	540

Table 9: DROPLET SIZING VALIDATION - NOZZLE #1

ALPHA [deg]	FILL [ml]	TIME [s]	FREQUENCY [Hz]	PHASE [cycles]	Rpda [μm]	Rmgd [μm]
5	7.8	15	103	1.450	1470	1060
5	8.1	15	103	1.419	1440	1080
5	9.4	15	104	1.494	1510	1130
5	6.8	15	80	1.438	1450	1100
5	7.8	15	90	1.491	1510	1110
5	7.9	15	98	1.451	1470	1090
5	7.6	15	98	1.014	1020	1070
5	7.8	15	98	1.020	1030	1080
5	8.4	15	98	1.015	1020	1110
5	8.2	15	106	0.962	970	1070
5	8.4	15	106	1.170	1180	1080

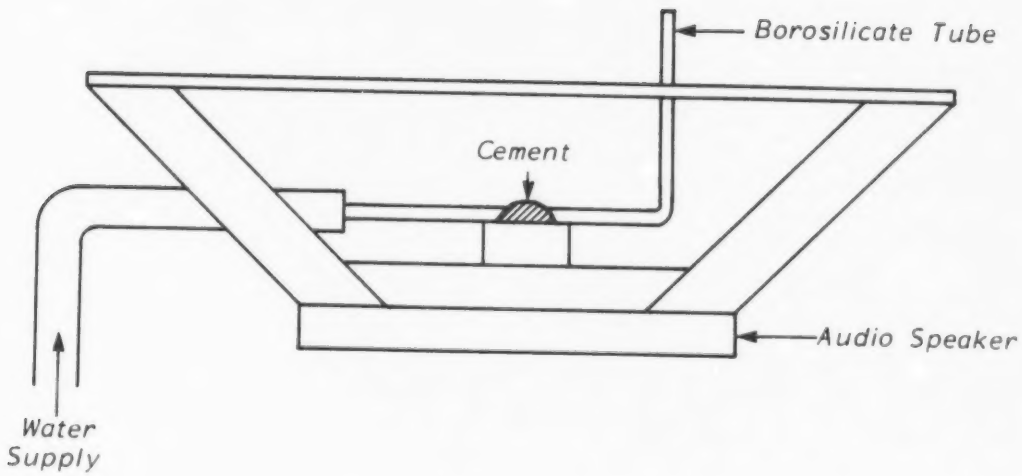

FIGURE 1
MAIN COMPONENTS OF MONODISPERSE DROPLET GENERATOR

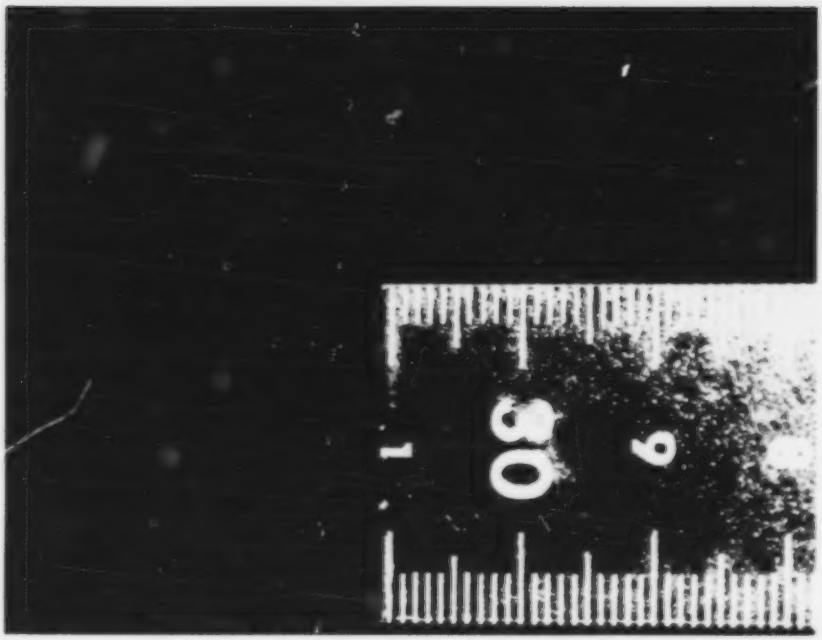

Figure 2: Photographic Measurement of Droplet Size

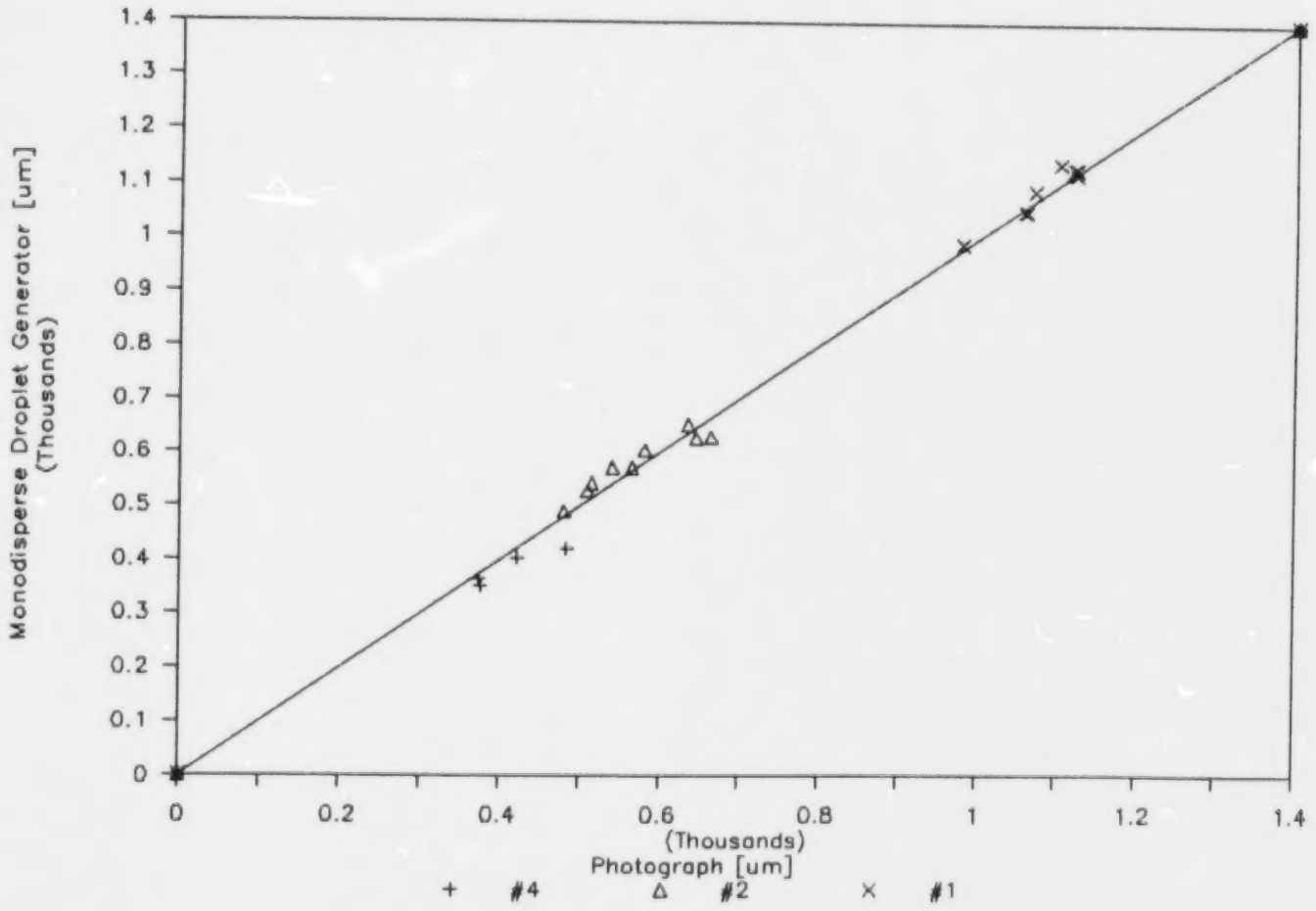

FIGURE 3

MONODISPERSE DROPLET GENERATOR, COMPARISON WITH PHOTOGRAPH

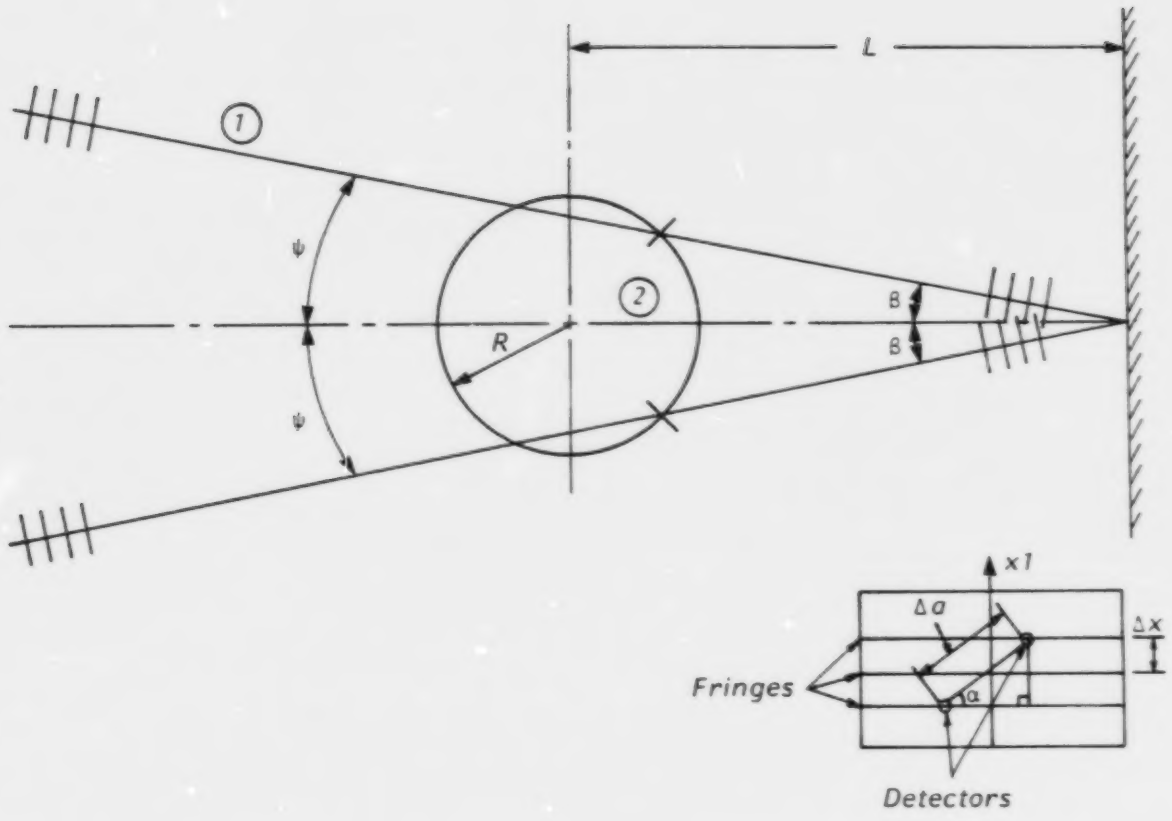

FIGURE 4
RAY TRACING CALCULATION

173113-RD

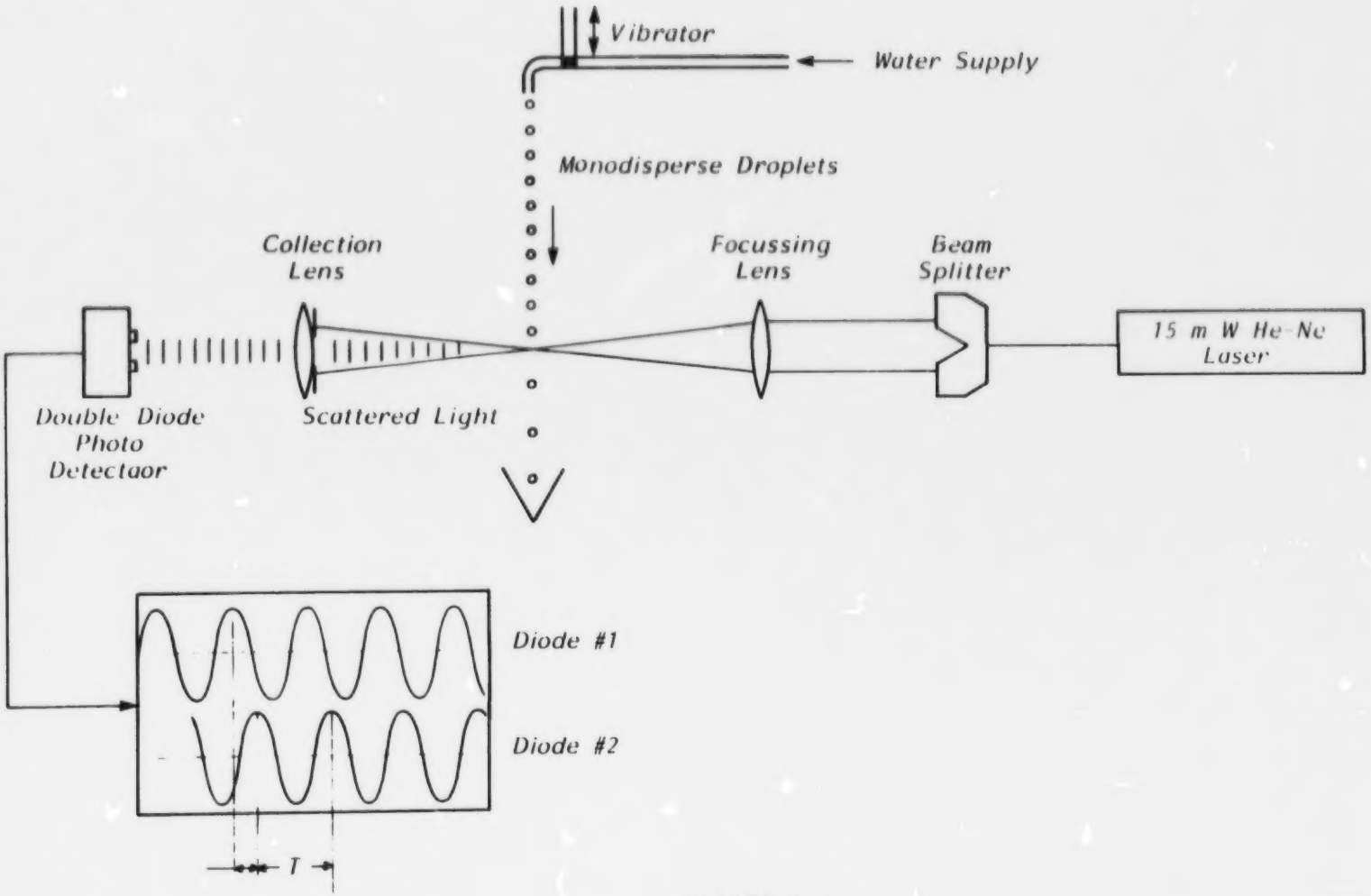

FIGURE 5

PHASE DOPPLER ANEMOMETER, OPTICAL ARRANGEMENT

173114-RD

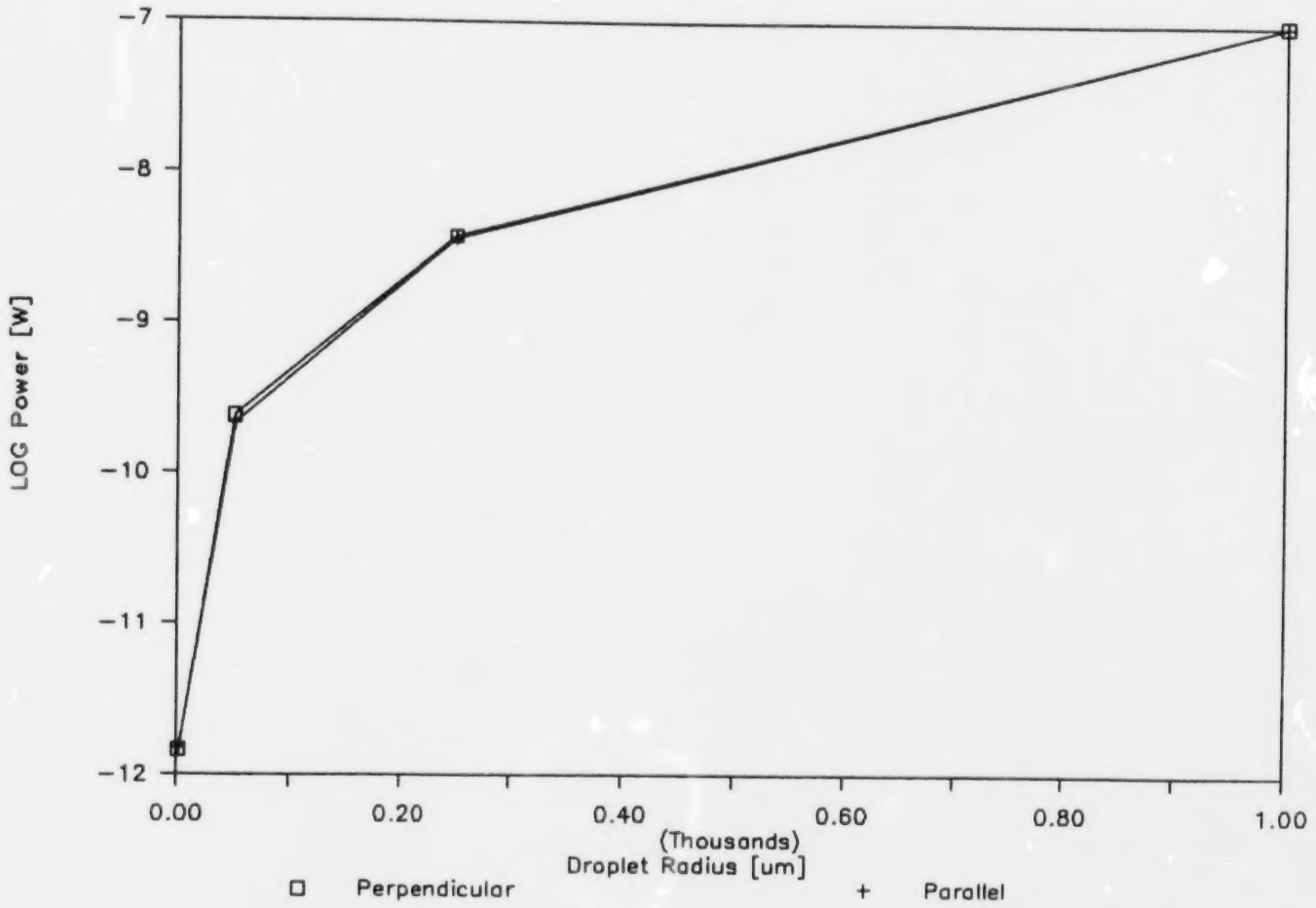

FIGURE 6
FORWARD LIGHT SHATTERING ON ONE DIODE

173115-RD

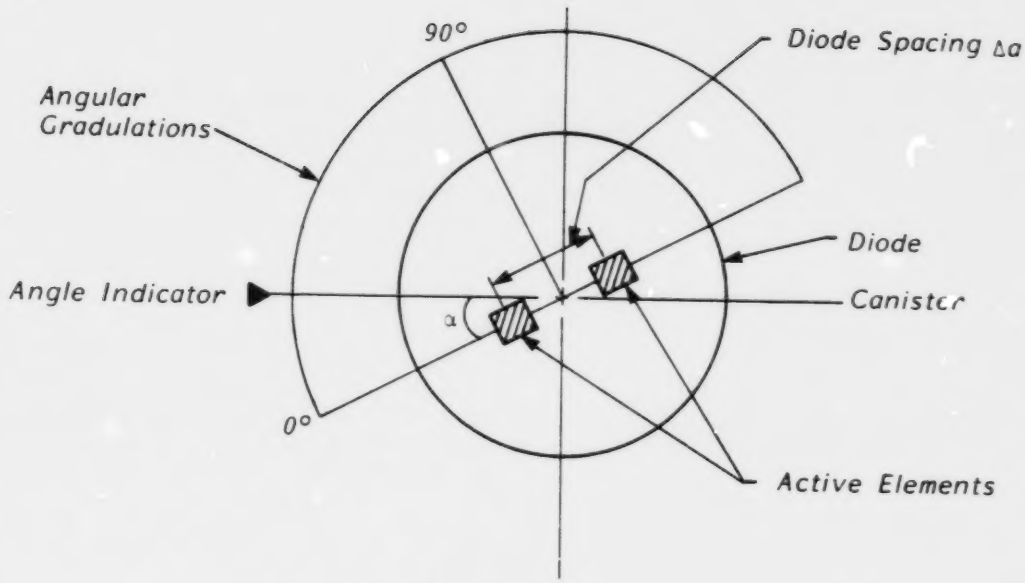

FIGURE 7
DOUBLE DIODE DETECTOR

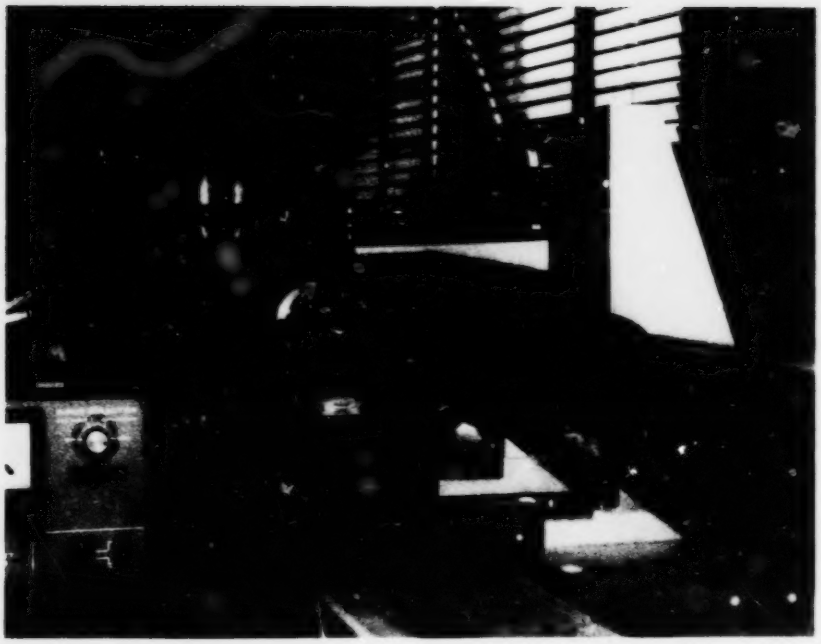

Figure 8: Equipment for Droplet Size Verification

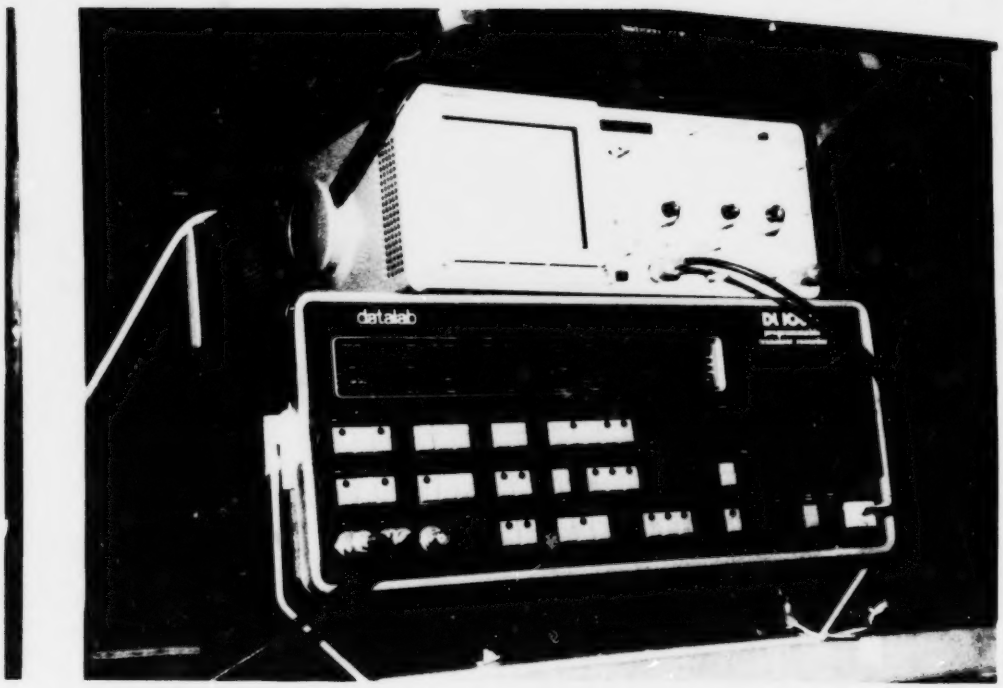

Figure 9: Waveform Recorder and Oscilloscope

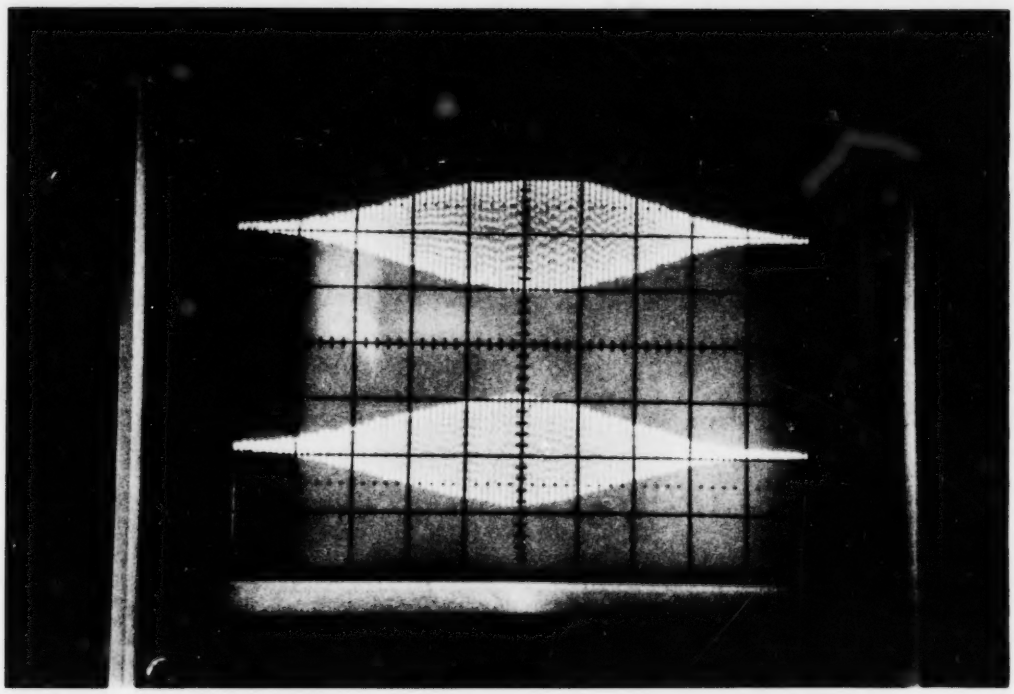

Figure 10: Pair of Doppler Bursts

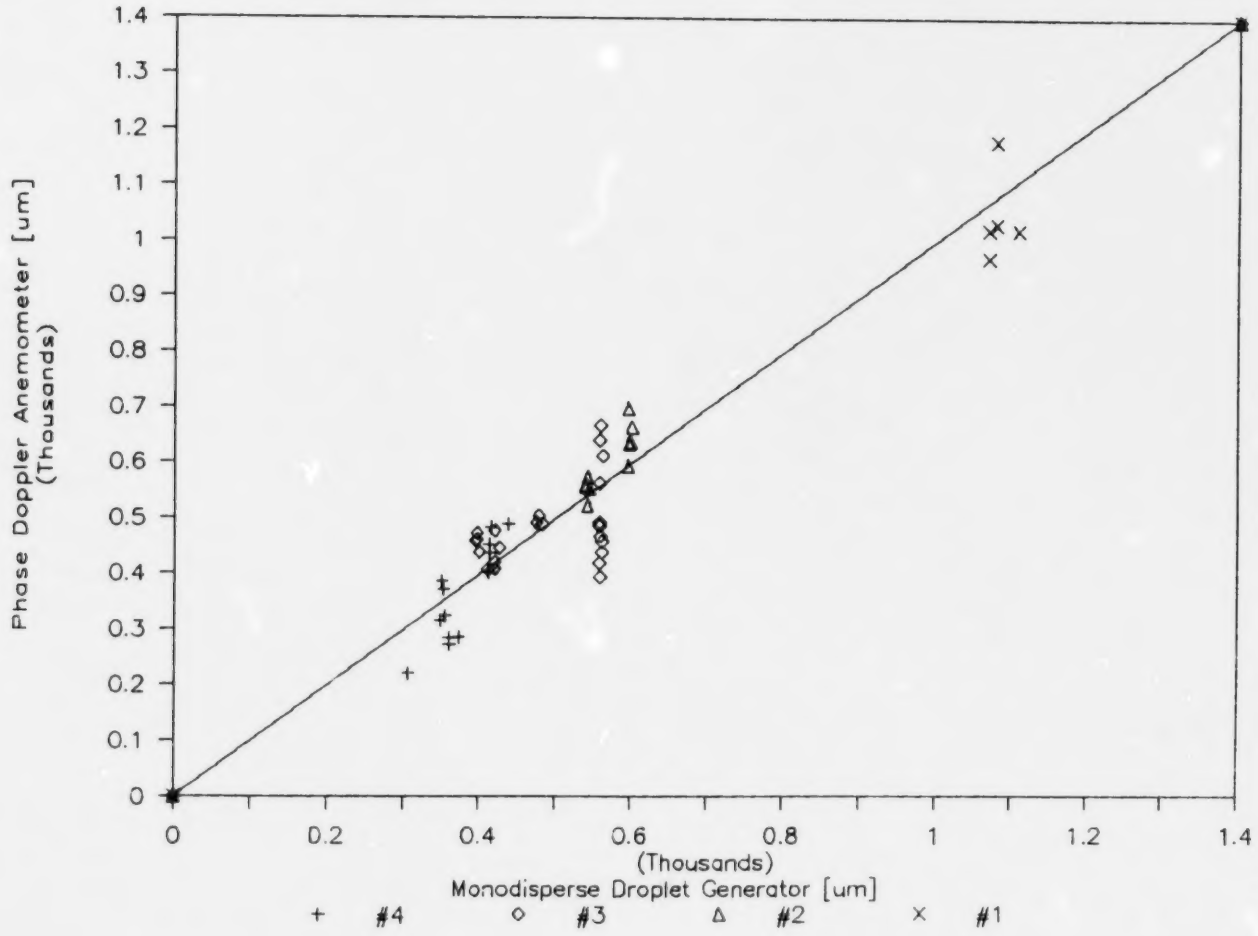

FIGURE 11

COMPARISON WITH DROPLET GENERATOR

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